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A Study on the Reliability of the Circuit Maintenance System-1B

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The Circuit Maintenance System (CMS)-1B has been developed to provide operational, administrative, and data base support to the trunk maintenance areas of the No. 4 ESS. In this paper, we investigate the reliability of the CMS-1B under the most stringent situation where six No. 4 ESSs are supported simultaneously. Our study results indicate that, with its current hardware arrangements, software structure, and administrative procedure, the CMS-1B can meet the reliability objective. Furthermore, the reliability of the CMS-1B is insensitive to an incremental change of its operating characteristics pertaining to the above three categories. We also provide a field-of-use guideline whereby the reliability of the CMS-1B can best be upgraded, if necessary. This guideline can be used by each CMS1-B site to decide whether its maintenance contract meets the response time requirement or its disk drive system needs to be replaced by a more reliable counterpart.

I. INTRODUCTION

The Circuit Maintenance System (CMS)-1B has a multiple office feature and can support up to six No. 4 ESSs* (for a description of No. 4 ESS and CMS, see Refs. 1 and 2). For a high degree of reliability, the CMS-1B employs a duplex computer system with an operating system designed to have fast reboot time and backup recovery capabilities.

In addition to its hardware and software structures, the reliability of the CMS-1B depends on the proficiency of the on-site corrective maintenance activities. Switching over from a faulty to a standby system, rebooting the system in the event of a software error, and repairing

* Since the total number of No. 4 ESS trunk terminations supported by a CMS-1B cannot exceed 160K, not more than one of these No. 4 ESSs is full-sized.

the faulty system are some maintenance activities required to bring the CMS-1B back to normal operation.

In this paper, we quantify some of the significant factors governing the CMS-1B reliability. More importantly, we evaluate whether the level of reliability attained by the CMS-1B would have any adverse impact on the No. 4 ESS served by it. We determine whether the current hardware arrangement, software structure, or administrative procedures are adequate from the No. 4 ESS's point of view. Should they be inadequate, we recommend some feasible means of upgrading the reliability of the CMS-1B.

The remaining portions of this paper are organized as follows. Section II provides a simplified description of the hardware arrangement of the CMS-1B. Because the CMS-1B can be viewed as consisting of a duplex and a simplex subsystem in tandem, the reliability models for these two subsystems are addressed in Sections III and IV, respectively. A reliability objective of the trunk maintenance operation of the No. 4 ESS is established in Section V. Section VI summarizes the input data required for the numerical computation of the reliability model. In Section VII, the reliability of the CMS-1B is measured against its objective as determined by the needs of No. 4 ESS. Sensitivity analyses are also presented. A field-of-use guideline by which the reliability of the CMS-1B can be upgraded is discussed in Section VII and, finally, conclusions are drawn in Section VIII.

II. CIRCUIT MAINTENANCE SYSTEM-1B

Figure 1 is a simplified CMS-1B hardware block diagram. The CMS-1B consists of a duplicated Digital Equipment Corporation (DEC) PDP

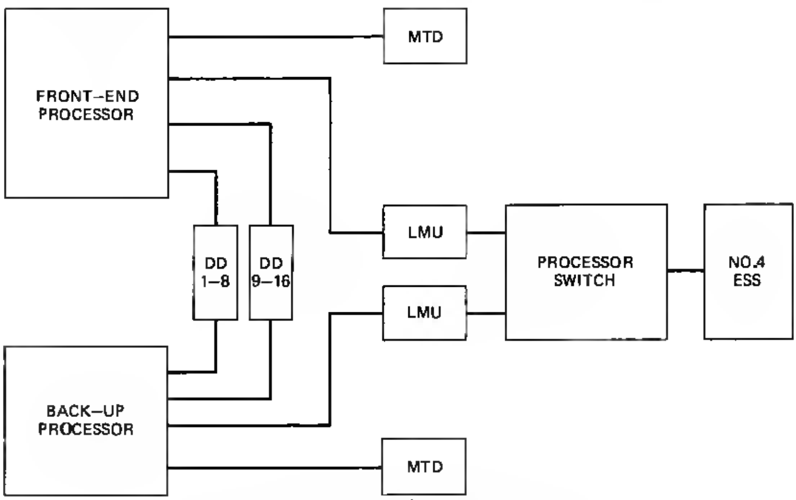

Fig. 1—Simplified CMS-1B block diagram.

11/70 processors, core memory, and mass storage devices in the form of disk drives (DD) and magnetic tape drives (MTD). The CMS-1B interconnects to and communicates with a No. 4 ESS through the data circuits and the line multiplex unit (LMU). The processor switch performs the function of switching the data circuits to the active LMU. For the sake of simplicity, other peripheral devices, such as the processor-controlled alarm circuits and the real-time clock, are not shown.

Primary system storage of the CMS-1B programs and data needed to facilitate trunk maintenance operations is provided by the disk controllers and disk drives. Since two disk drives are required for each No. 4 ESS, as many as 12 disk drives are being actively used. As the disk drive system is not duplicated, two hot spare or powered-up standby drives are provided to maintain a high level of reliability.

The CMS-1B can be physically divided into two independent subsystems, the duplex and the simplex systems. The simplex system represents the disk drive system while the duplex one signifies the rest of the CMS-1B. These two independent subsystems are connected in series, and a malfunction in either subsystem will affect the normal operation of the CMS-1B. Mathematically, if the availabilities of the duplex and the simplex systems are denoted by A_d and A_s, respectively, the availability of the CMS-1B is given by

$$A = A_d A_s. \tag{1}$$

Conversely, the unavailability of the CMS-1B is given by

$$U = 1 - A, \tag{2}$$

which signifies the fraction of downtime expressed in hours per year or in minutes per day.

The system unavailability of (2) will henceforth be used as a measure of the degree of reliability of the CMS-1B. To quantify it, the individual availabilities of the duplex and the simplex systems must first be determined.

III. DUPLEX SYSTEM

The normal operation of this subsystem can be interrupted by either a hardware or a software problem. The hardware-related problems include those associated with the central processor units, the memory banks, the magnetic tape drives, the disk controllers, or the line multiplex units. In other words, if the failure rate of the ith hardware unit is λ_i, the overall hardware failure rate λ_h of the duplex system is computed as

$$\lambda_h = \sum_{i=1}^{\ell} \lambda_i, \tag{3}$$

where ℓ signifies the total number of individual hardware units.

When a hardware failure occurs, the CMS-1B can be brought back to its normal operation almost instantly by switching from the faulty to the standby unit, if one is available. The average lengths of time taken by a repair person to report to the CMS-1B site and to repair the faulty unit are called the mean response time, $1/\mu_t$, and the mean repair time, $1/\mu_r$, respectively.

Unlike the hardware problems, software problems are less well-defined and their failure and repair statistics are not readily available. In general, software problems of a mature system are expected to be diagnosed and rebooted within a short time interval. Rectification of some software problems such as a debilitating data base requires more than a reboot action and therefore a longer time period. However, characterization of these less frequent but more severe software problems is presently not well understood and is therefore excluded from our reliability study. With this assumption, the software failure rate is represented by λ_s and the corresponding mean reboot time by $1/\mu_b$.

3.1 System states

In view of the front-end and the backup system arrangement and the possible occurrence of a hardware and a software failure, the duplex system has a large number of possible system states. The various states of the duplex system are summarized in Table I. Both the front-end and backup systems as well as the software are operative in State 1. While the software is still in operation, the backup and the front-end system become inoperative in States 2 and 3, respectively. However, the CMS-1B is still in its normal operation in these two states. The remaining states signifity other possible combinations.

Based on the states defined in Table I, the CMS-1B is available in States 1 to 3 and unavailable in States 4 to 8.

3.2 State transitions

All the possible transitions interconnecting the eight states are diagrammed in Fig. 2. Three possible transitions emanate from State 1 as a result of a front-end, a backup, or a software failure. States 2, 3,

Table I—System states of the duplex system

State	Front-end System	Back-up System	Software
1	Up	Up	Up
2	Up	Down	Up
3	Down	Up	Up
4	Down	Up	Down
5	Up	Up	Down
6	Up	Down	Down
7	Down	Down	Up
8	Down	Down	Down

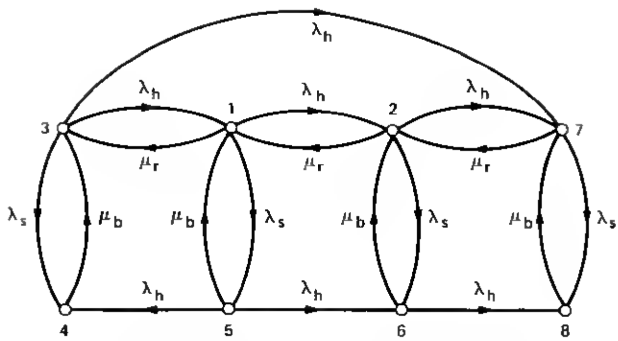

Fig. 2—State transition diagram of the duplex system.

and 6 can return to State 1 through repair or reboot action. States 4, 5, 6, and 8 indicate a software failure and can return to their respective preceding states by rebooting. Both the front-end and the backup systems suffer a hardware failure at States 7 and 8, wherein the CMS-1B would be inoperative for a long period of time.

3.3 Mathematical representation

For mathematical simplicity, we assume that both the hardware and the software failures are independent and Poisson distributed. We also assume that the times to switchover, to respond to a service call, to repair, and to reboot are exponentially distributed. Using these assumptions and denoting p_i as the steady-state probability of being in State i of the duplex system, we can derive from Fig. 2 a set of first-order differential equations:

$$\begin{aligned}
\dot{p}_1 &= -(2\lambda_h + \lambda_s)p_1 + \mu_r p_2 + \mu_r p_3 + \mu_b p_5 \\
\dot{p}_2 &= \lambda_h p_1 - (\lambda_h + \lambda_s + \mu_r)p_2 + \mu_b p_6 + \mu_r p_7 \\
\dot{p}_3 &= \lambda_h p_1 - (\lambda_h + \lambda_s + \mu_r)p_3 + \mu_b p_4 \\
\dot{p}_4 &= \lambda_s p_3 - \mu_b p_4 + \lambda_h p_5 \\
\dot{p}_5 &= \lambda_s p_1 - (2\lambda_h + \mu_b)p_5 \\
\dot{p}_6 &= \lambda_s p_2 + \lambda_h p_5 - (\lambda_h + \mu_b)p_6 \\
\dot{p}_7 &= \lambda_h p_2 + \lambda_h p_3 - (\lambda_s + \mu_r)p_7 + \mu_b p_8 \\
\dot{p}_8 &= \lambda_h p_6 + \lambda_s p_7 - \mu_b p_8,
\end{aligned} \tag{4}$$

where

$$\sum_{i=1}^{8} p_i = 1.$$

Solving these eight differential equations using standard techniques,

we compute the availability of the duplex system by summing the "up" probabilities as

$$A_d = \sum_{i=1}^{3} p_i. \tag{5}$$

IV. SIMPLEX SYSTEM

The disk drive system is said to be inoperative whenever a disk drive fails or some data are lost due to such mishaps as a headcrash. The failure and headcrash rates of the disk drives, active and spare, are denoted by λ_f and λ_c, respectively. It should be pointed out that, unlike the duplex system, when the simplex system is inoperative, only one No. 4 ESS is affected.

In the event of a disk drive failure, the simplex system can be brought back to normal operation by moving the disk pack involved from the faulty disk drive to a spare one, if one is standing by. The average amount of time required to perform this changeover is called the mean switchover time, $1/\mu_s$.

In the case of a headcrash, the lost data must first be reconstructed before switching over to a spare disk drive. The average length of time required to rebuild the data base is called the mean rebuild time, $1/\mu_c$.

It is assumed that all faulty disk drives require the same amount of repair time. In other words, if the mean response time and the mean on-site repair time for a faulty disk drive are c and r, respectively, the average total repair time of k faulty disk drives is given as

$$\frac{1}{\mu_k} = c + kr. \tag{6}$$

4.1 System states

For the sake of generality, we assume that n active and m spare disk drives are in the simplex system. The various possible states of the simplex system are tabulated in Table II. As a result of a disk drive failure (State 2) or a headcrash (State 2′), there are $(n-1)$ active, m spare and one faulty disk drives in these two states. At State 3, a spare disk drive has been activated and there are consequently n active, $(m-1)$ spare and one faulty disk drives in the simplex system. Similar evolution continues until there is no spare disk drive left in State $(2m+1)$. At this point, the simplex system would become inoperative for a relatively long period of time if a failure or a headcrash occurred resulting in the simplex system being in States $(2m+2)$ or $(2m+2)'$, respectively.

It can be seen that there are $(3m+3)$ possible states in the simplex systems and all the even-numbered states signify that the normal operation of the simplex system is disrupted.

Table II—System states of the disk drive system

State	No. of Disk Drives Active	Spare	Faulty
1	n	m	0
2	n−1	m	1
2′	n−1	m	1
3	n	m−1	1
4	n−1	m−1	2
4′	n−1	m−1	2
5	n	m−2	2
6	n−1	m−2	3
6′	n−1	m−2	3
•	•	•	•
•	•	•	•
•	•	•	•
2m+1	n	0	m
2m+2	n−1	0	m+1
(2m+2)′	n−1	0	m+1

4.2 State transition

The state transition diagram of the simplex system is depicted in Fig. 3. A transition takes place between States 1 and 2 or 2′ after a disk drive fails or a headcrash occurs. By switching over or rebuilding the data base, the simplex system is brought back to normal operation at State 3. State 3 can return to State 1 after performing the necessary repair function. A similar cycle may also be initiated at State 3 and terminated at State 5. This repetitive pattern comes to an end at State

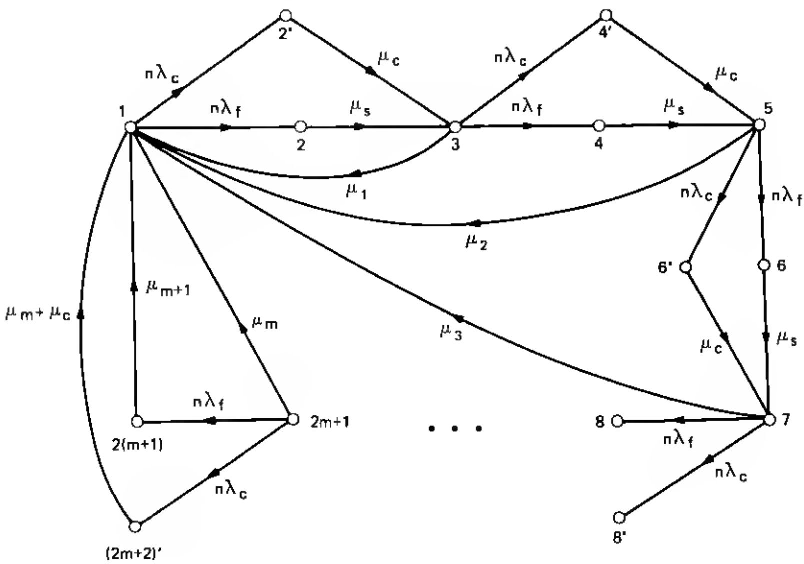

Fig. 3—State transition diagram of the disk drive system.

$(2m + 1)$, where there is no spare disk drive left. At this point, another disk drive failure or headcrash will render the simplex system inoperative until the faulty drives are repaired.

It should be pointed out that not all the transitions identified in Fig. 3 are unique. For example, State 5 can return to State 1 by a direct transition or by first returning to State 3. However, the difference in the end result between using these two different paths can be shown to be small.

4.3 Mathematical representation

As before, we assume that both the disk drive failures and the headcrashes are Poisson distributed. The time to switchover, to rebuild a data base, or to repair a faulty disk drive are exponentially distributed. Defining q_i as the probability of being in State i of the simplex system, we can derive from Fig. 3 a set of first-order differential equations:

$$\dot{q}_1 = -n\bar{\lambda}q_1 + \left(\sum_{k=1}^{m} \mu_k q_{2k+1}\right) + \mu_{m+1}q_{2m+2} + (\mu_m + \mu_c)q_{(2m+2)'}$$

$$\left.\begin{aligned} \dot{q}_{2i} &= n\lambda_f q_{2i-1} - \mu_s q_{2i} \\ \dot{q}_{2i'} &= n\lambda_c q_{2i-1} - \mu_c q_{2i'} \\ \dot{q}_{2i+1} &= \mu_s q_{2i} + \mu_c q_{2i'} - (n\bar{\lambda} + \mu_i)q_{2i+1} \end{aligned}\right\} \quad 1 \le i \le m$$

$$\begin{aligned} \dot{q}_{2m+2} &= n\lambda_f q_{2m+1} - \mu_{m+1}q_{2m+2} \\ \dot{q}_{(2m+2)'} &= n\lambda_c q_{2m+1} - (\mu_m + \mu_c)q_{(2m+2)'} \end{aligned} \tag{7}$$

where

$$\bar{\lambda} = \lambda_f + \lambda_c$$

and

$$\sum_{i=1}^{m+1} (q_{(2i-1)} + q_{2i} + q_{2i'}) = 1.$$

Since each No. 4 ESS occupies two disk drives and there are a total of n of these disk drives, the probability is $2/n$ that a No. 4 ESS is affected when the simplex system is inoperative.* Thus, the unavailability of the simplex system from the viewpoint of a single No. 4 ESS is

$$U_s = \frac{2}{n} \sum_{i=1}^{m+1} (q_{2i} + q_{2i'}). \tag{8}$$

The availability of the simplex system is therefore given by

$$A_s = 1 - U_s. \tag{9}$$

* This is the worst case, as a small No. 4 ESS occupies only one disk drive.

V. RELIABILITY OBJECTIVE

Before quantifying the degree of reliability of the CMS-1B, we first establish the reliability objective required for the trunk maintenance operation of the No. 4 ESS. During a CMS-1B outage, necessary functions at the trunk test positions would be inoperative, and trunk trouble reports would be misplaced. The trunk maintenance operation would become so awkward that it would essentially be halted. A stoppage in trunk maintenance operation will eventually affect the service of the No. 4 ESS. Thus, a CMS-1B outage affects the integrity of not only the CMS-1B itself but also the No. 4 ESS.

Based on these adverse effects, a downtime objective for the CMS-1B was established. This downtime objective represents the limit above which CMS-1B outages will have measurable effects on the service of the No. 4 ESS. To minimize the adverse impact of CMS-1B outages, a downtime objective of three minutes per day was judged to be a reasonable system goal.[3] It should be pointed out that the stringent downtime requirement of three minutes per day is applicable only to unexpected outages. Scheduled outages such as preventive maintenance activities are not included, as they can take place during noncritical hours.

VI. INPUT DATA

Essentially, two categories of input data are required for the numerical computation of the reliability model described in Sections III and IV. The first category of input data is the mean times between hardware failures and between software failures, while the other one is the mean times to perform corrective maintenance functions. Wherever possible, the necessary data were gathered from the existing CMS-1B sites through the data base maintained by the minicomputer reliability group at Columbus, Ohio. For those input data which were not available from the data base, we estimated their normative values based on the experience of the personnel from the CMS development group at Holmdel, New Jersey and the CMS field support group at Merrimack Valley, Massachusetts. However, we will vary the value of each of the input data so as to evaluate its impact on the reliability of the CMS-1B.

6.1 Mean time between failures

Based on the limited downtime data reported by personnel from the existing CMS-1B sites, some failure statistics on various hardware components of the PDP 11/70 computer for the last 12 months has been compiled. With the use of these statistics and eq. (3), the mean times between simplex hardware failures in the duplex and in the simplex systems are calculated to be 40 days and 3.4 months, respectively.

No data were available for estimating the mean times between headcrashes and between software errors. However, a headcrash rate of once every 1.5 years and a minor software error rate of once every week were judged to be reasonable, normative values. These values will be perturbed in a later section to determine their effects on the overall reliability of the CMS-1B. The failure statistics to be used in this reliability study are summarized in Table III.

6.2 Corrective maintenance

The average amount of time devoted to each corrective maintenance activity depends to a large extent on the on-site coverage of the CMS-1B. For example, the hardware repair function is generally covered by a maintenance contract with DEC which might govern the maximum response time of its repair crew. On the average, a one-half of one day response time and a three-hour on-site repair time were experienced. The remaining corrective maintenance activities are the responsibility of the craftsperson on duty. It was estimated that the average time taken to reboot the system, to change over a disk drive, and to rebuild a disk pack are 10 minutes, 15 minutes, and 1 hour, respectively. In addition to performing the corrective function, these time intervals include the detection and the identification of the system unit and problem involved.

VII. RESULTS

While the CMS-1B might serve fewer than six No. 4 ESSs, our reliability results are directed primarily to the worst case with six No. 4 ESSs. In the latter case, there are a total of 12 active and two spare disk drives in the CMS-1B, with each No. 4 ESS occupying two active disk drives. With the use of the input data defined in Section VI and the reliability model characterized in Sections III and IV, the mean downtime of the CMS-1B is found to be 2.8 minutes a day, and the mean time between the CMS-1B outages is 4.6 days. It should be pointed out that there is a nonzero probability that both the front-end and the backup systems are out of service or one of the active disk drives experiences a hardware problem after the two spare ones have been used. Under this situation, the CMS-1B would suffer an outage for

Table III—Mean time between failures statistics

Item	MTBF
Hardware of duplex system	40 days
Software	7 days
Disk drive	3.4 months
Headcrash	1.5 years

as long as 15 hours. However, this extended outage has a probability of occurring only once every 2.5 years.

7.1 Sensitivity Analysis

It can be seen that, under the study assumptions, the CMS-1B satisfies its reliability objective. However, because the reliability is close to the limit, the sensitivity of this reliability to changes in some of the input data should be determined.

7.1.1 Mean Response Time

The sensitivity of the reliability of the CMS-1B to the mean response time of a repair crew is depicted in Fig. 4. The upper and lower curves signify a mean switchover time of 30 and 15 minutes, respectively, while the straight line represents the CMS-1B downtime objective of three minutes per day. As expected, the mean CMS-1B downtime is an increasing function of the mean response time. The rate of increase becomes considerably steeper when the mean response time is in excess of one-half day. On the other hand, the mean CMS-1B downtime is relatively insensitive to the change in the mean switchover time. For example, a 10-percent increase in the mean response time constitutes a 6-percent increase in the mean CMS-1B downtime, whereas the same amount of increase in the mean switchover time brings about only a 1-percent change in the mean CMS-1B downtime.

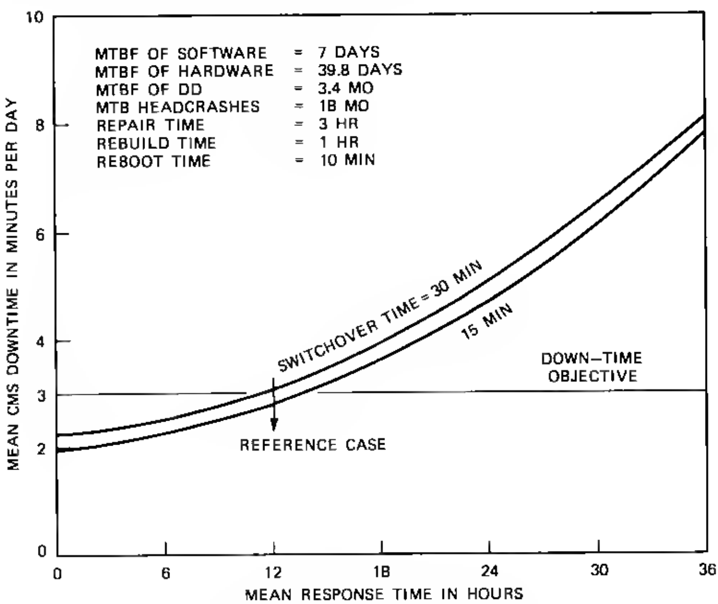

Fig. 4—Sensitivity to mean response time.

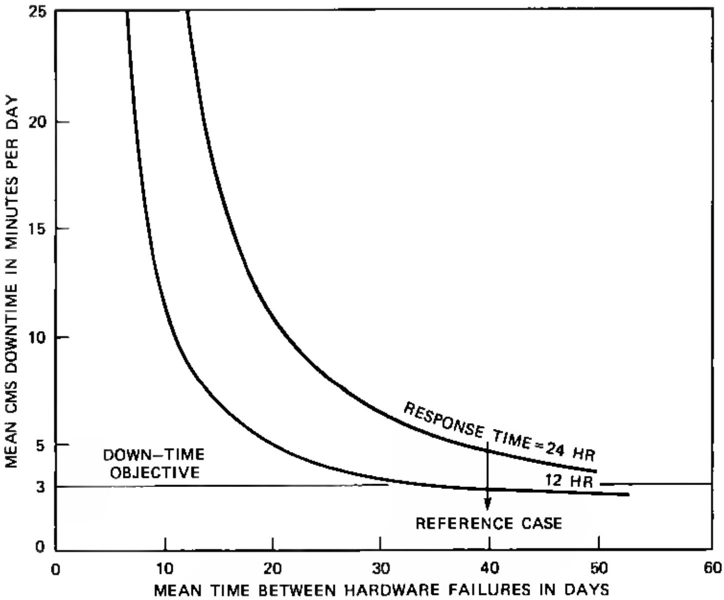

Fig. 5—Sensitivity to MTBF of hardware.

7.1.2 Mean time between failures of hardware

As shown in Fig. 5, the mean CMS-1B downtime is inversely proportional to the mean time between hardware failures in the duplex system with a mean response time of one-half day. The mean CMS-1B downtime is approaching its asymptotic value rapidly after the MTBF becomes larger than 40 days (signified by a vertical bar). For a mean response time of one day, the speed of reaching its asymptotic value is somewhat slower. To meet the CMS-1B downtime objective, a 10-percent decrease in the MTBF with an average response time of one-half day is tolerable.

7.1.3 Mean time between failures of software

The behavior of the mean CMS-1B downtime with varying mean times between software errors is similar to its hardware counterpart. The speed of reaching the asymptotic region, or the insensitive region, is dependent on the value of the mean reboot time. Figure 6 indicates the required reduction in reboot time to compensate for a higher software failure rate and vice versa. This implies that, even if the CMS-1B software were experiencing a relatively higher failure rate, say, once a day, as long as this software error could be rectified within a short period of time, say, 30 seconds the CMS-1B downtime objective could still be met. Figure 6 also indicates that an occurrence of a severe

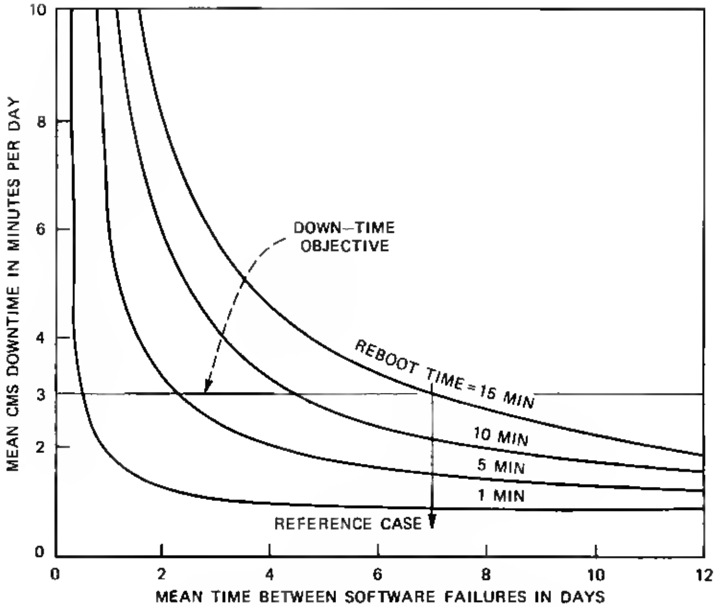

Fig. 6—Sensitivity to MTBF of software.

software problem whose reboot time is in the order of hours would not meet the CMS-1B reliability objective.

7.1.4 Mean time between failures of disk drives

Except for a relatively wider asymptotic region in the vicinity of its operating value, the mean time between disk drive failures poses a similar impact on the mean CMS-1B downtime as the hardware in the duplex system. For example, even a 25-percent decrease in the mean time between the disk drive failures would not result in any significant change in the mean CMS-1B downtime.

7.1.5 Mean time between headcrashes

The relationship between the mean time between headcrashes and the mean rebuild time is qualitatively similar to that between the mean time between software errors and the mean reboot time. However, it follows from Fig. 7 that a mean rebuild time in excess of one hour would demand a rather high compensation from the headcrash rate.

7.1.6 Number of spare disk drives

The sensitivity of the mean CMS-1B downtime to the number of spare disk drives for different mean response times is shown in Fig. 8. It is clear that, while more than one spare disk drive is desirable, more than three spares are not warranted.

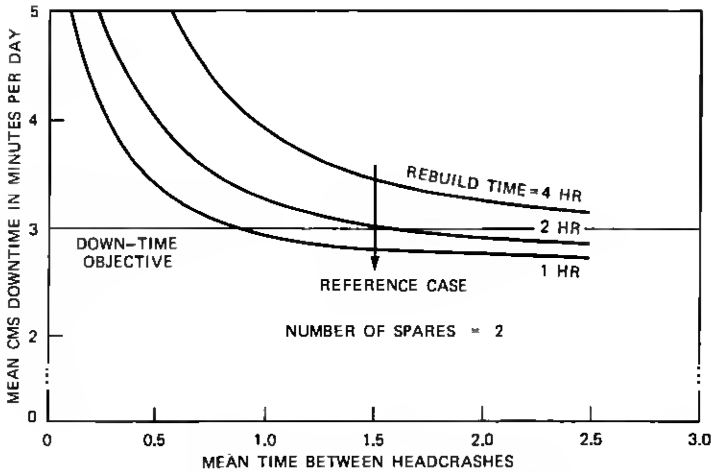

Fig. 7—Sensitivity to MTBF headcrashes.

VIII. FIELD OF USE GUIDELINES

The reliability of the CMS-1B is clearly dependent on its operating characteristics governed by such variables as the mean times between various failures and the mean times to perform appropriate corrective maintenance functions. The sensitivity analyses conducted in Section 7.1 indicate that many sets of operating characteristics exist that also satisfy the reliability objective required by the No. 4 ESS. There are a

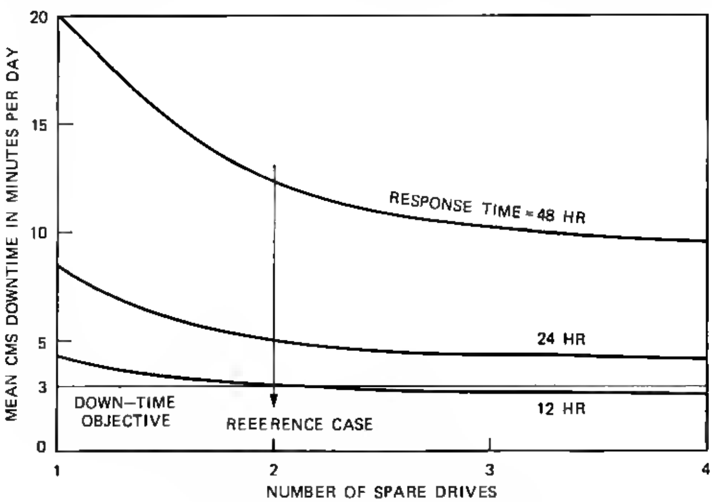

Fig. 8—Sensitivity to number of spare drives.

number of degrees of freedom within which the operating characteristics of the CMS-1B can be constructed so as to satisfy its reliability objective. For example, a more expensive maintenance contract would ensure a faster response time of the repair crew, a better designed disk drive system would reduce the number of breakdowns and headcrashes, a faster magnetic tape drive would shorten the time to rebuild data base, and so on.

It is therefore beneficial to provide some field-of-use guidelines with which the most appropriate operating characteristics can be selected for each CMS-1B. To do this, we will rank-order the degree of impact of each of the variables upon the reliability of the CMS-1B. The quantitative effect of each variable is measured by the percent change in the normative value of the variable. It should be noted that, in view of the highly nonlinear nature of the operating characteristics of the CMS-1B, this quantitative measure is valid only in the vicinity of the operating region. For example, the effect of the mean response time on the reliability of the CMS-1B is considerably larger in the 12-hour mean response time region than that in the 6-hour one. The degree of impact of each of the variables upon the reliability of the CMS-1B is summarized in Table IV.

It can be seen that the most sensitive, or the most effective, variable for improving the reliability of the CMS-1B is the mean response time. Lower hardware and software failure rates and faster reboot times are almost as effective a way of upgrading the system reliability. The mean time between software errors and the mean time to reboot have equal impact on the system reliability, and their effects are interchangeable. Moreover, whenever a major software problem such as a data base mutilation occurs, the CMS-1B reliability objective will not be satisfied.

Insofar as system reliability is concerned, Table VI can be used as a guideline for selecting the appropriate maintenance contract, specifying more reliable hardware, etc.

Table IV—Development guidelines

10% Increase of Normal Value	% Increase of Down Time of 3 min/day
Response time	5.6
Hardware failure rate	5.0
Software failure rate	4.7
Reboot time	4.7
DD failure time	2.7
Repair time	1.5
Switchover time	1.0
Headcrash rate	0.9
Rebuild time	0.7

IX. CONCLUSION

Based on the study assumptions reported here, CMS-1B is able to meet the objective reliability as required by the No. 4 ESS. To achieve this reliability goal, the following operating characteristics are required of the CMS-1B:

(*i*) Two spare disk drives standing by for a maximum of 12 active disk drives.

(*ii*) Mean time between duplex hardware failure of 40 days.

(*iii*) Mean time between disk drive failure of 3.5 months with less than 15 minutes of mean switchover time to a spare.

(*iv*) Mean time between headcrashes of 1.5 years with less than 1 hour of mean data rebuild time.

(*v*) Little or no severe software problems and the mean time between minor software errors of one week with less than 10 minutes of mean reboot times.

(*vi*) Mean response time of less than one-half day and mean on-site repair time of less than three hours.

Each of these six operating characteristics can be achieved by the current CMS-1B. Furthermore, the reliability of the CMS-1B is insensitive to as much as a 10-percent increase in any one of these operating characteristics.

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